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The development of solar PV in The Netherlands: A case of survival in unfriendly contexts

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ABSTRACT

This paper reviews the developments of solar photovoltaic (PV) technology in The Netherlands. Despite the recent boom in PV industries and its global deployment, The Netherlands has up to now not experienced major growth in the diffusion of PV electricity generation. But this is only part of the story. This paper focuses on the question why PV is still around in The Netherlands at all despiteits, at times, harsh policy and socio-economic contexts. It builds upon a recently developed framework from the field of transition studies that distinguishes between shielding, nurturing and empowerment of sustainable innovations. A descriptive historical review is combined with an analysis of niche space that shows how PV advocates have been able to strategically secure and shape protective measures over four decades in the context of harsh regime selection environments. The paper suggests how further analyses using this shielding-nurturing-empowerment framework can benefit from this exploratory study into PV innovation in The Netherlands.

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1. Introduction

Solar photovoltaic technology (PV) has been around for a long time in The Netherlands. Academic visions about the technology as an energy source date back as far as the 1920s. This potential was the subject of serious academic assessment in the 1950s, around which time it was already being applied as a power source in the space industry [1]. Since the oil crises and increasing environmental awareness of the 1970s, it has been a staple in future energy scenarios and visions among science, business and policy actors alike. In 1990, the Dutch government hailed solar PV as 'likely the most important renewable energy source after 2010' [2]. Indeed, over the past few years many international studies reported on drastic price reductions, booming markets and flourishing industries [3] [1].

Nevertheless in 2010, its share in total Dutch renewable electricity production (wind, biomass, hydro and solar) was still only a very modest 0.6%, while its contribution to the total Dutch electricity production was an order of magnitude smaller still at slightly under 0.05% (source: Statistics Netherlands—CBS). An obvious question is: what had gone wrong? Many possible answers exist to the question of why renewable diffuse so slowly, including poor technical and economic performance, failing policy and failing innovation systems [4]. A perhaps less obvious but no less interesting question is why, after so many years of development with ostensibly so little success, solar PV in The Netherlands is still around *at all*. One interesting answer to this 'reverse'question comes from socio-technical transitions literature, which argues that innovations that are not competitive yet with mainstream selection environments can survive and develop in protective spaces ('niches') for extended periods of time, because these spaces exempt them from various selection pressures emanating from dominant socio-technical regimes [5,6]. These regimes are interlinked webs of established technologies, practices, meanings, markets, policies, infrastructures and constitute multi-dimensional selection environments for innovations aiming to realize a similar societal function [7]. Regimes typically select against radical innovations because they display a mismatch with the extant 'way of doing things' across the multiple dimensions. Consequently, regimes tend to favor incremental changes over more transformative innovations.

But while this *effect* of protective spaces has been thoroughly documented in a burgeoning literature on strategic niche management (e.g. [8,9]), systematic accounts of *how* such protective spaces are created and maintained or removed over time are sparse. Recently, Smith and Raven [10] have proposed that relations between (dynamics in) protective space, innovation processes and broader processes of transformation should be understood through processes of *shielding, nurturing* and *empowering*. They argued that shielding is about multi-dimensional work aimed at shaping a protective space by exempting an innovation from some mainstream selection environments; nurturing is about work aimed at improving an innovation's socio-technical performance; and empowering is about work aimed either at altering mainstream selection environments (e.g. incorporating sustainability criteria) or at making innovations competitive within existing mainstream selection environments. They conclude their conceptual paper with a call for empirical research interrogating their framework with empirical cases. This paper answers that call.

Moreover, it aims to explore the usefulness of these concepts of shielding, nurturing and empowering with a specific research question in mind: how has solar PV technology in The Netherlands managed to survive (albeit in relatively small numbers) despite, as we shall see, harsh policy and socio-economic contexts. This makes PV an interesting case for Smith and Raven's framework, because harsh contexts, we expect, are an extreme case for studying the dynamics of protective spaces: activities of innovation advocates to create, maintain or abolish protective spaces will be more visible and leave more empirical traces, because the actors will have to work much harder, compared to cases of rather supportive and uncontested policy environments. Hence, this paper examines to what extent these three concepts indeed help understand the dynamics of protective space by applying the concepts to the Dutch solar PV case.

2. Conceptual framework and methodology

Questions about *how* a social phenomenon emerges, develops, grows, or terminates over time are typically addressed using 'process theories' [11,12]. In this context, 'process' refers to a description of how things develop and change [13]. Process theories view the social world as being made of entities that participate in sequences of *events*, which are not exogenous occurrences but rather 'what key actors do or what happens to them' [11]. Process theories focus on narratives instead of variables, but the objective is explicitly not to simply write stories containing sequences of event. Instead, the objective is to turn a case *history* into a case *study* [14] through an explicit attempt at interpreting and explaining the process under study:

> (…) to describe a process, one needs event sequences. But to explain a process one needs to identify the generative structures that enable and constrain it ([15]:p. 722).

Process theories thus aim at "event-driven explanation of the temporal order and sequence in which a discrete set of events occur" based on a historical description ([16]:p. 145). To arrive at a process theory, historical descriptions thus need to be recontextualized in a specific conceptual frame ([17]:p. 201). Analytical concepts serve as vehicles for such recontextualisation. In this paper, the social phenomenon of interest is protective space, and the structuring devices proposed by Smith and Raven [10] for recontextualizing the historical developments are the analytical concepts of shielding, nurturing and empowering. The following sections discuss the protocol used for doing so.

2.1. Historical descriptions

We compiled a chronology by arranging key events in the development of Dutch solar PV in their order of occurrence in time (i.e. 'building the skeleton'). The events constituting this timeline which spans the better part of a century were derived

[1] Reasons behind this boom and whether these price reductions signal a healthy or unhealthy long-term growth of the world-wide PV sector are contested. PV industries are struggling to survive because revenue is too low, which results from overproduction due to uncertain demand worldwide. The latter itself results from the fact that some of the more profitable government support programs have been reduced or are being renegotiated, e.g. in Germany and Portugal.

from heterogeneous primary as well as secondary sources, such as histories of renewable energy in The Netherlands, academic publications, reports by consulting agencies and government institutions, news articles, press releases and presentations prepared by solar PV insiders.

We then expanded this list of events by describing how, by whom, and to what effect these events were brought about (i.e. 'adding the meat'). For the period before 1990, this detailed case history builds largely on the excellent and comprehensive history of renewable energy in The Netherlands by Verbong et al. [18]. For the period after 1990, we relied on the aforementioned collection of primary and secondary sources which we triangulated with five semi-structured interviews with actors who have a 'birds eye view' of (certain aspects of) these developments[2].

In the resulting case history, we distinguished five heterogeneous *spaces* in the Dutch solar PV developments which emerged at different points in time, interacted, and rose and fell in prominence. These spaces are actor categories constituted by actors' discursive practices: PV actors use them to refer to and to make sense of prominent 'sites of PV action'.[3] The five spaces identified are *research and development*, *PV industry* (*PV cell manufacturing as well as manufacturing of complementary technologies*), *autonomous PV systems*, *building-integrated PV* and *retrofitting PV*. It is immediately clear that the five spaces are heterogeneous: they include, in varying degrees, socio-cognitive, institutional, spatial, and functional dimensions. But we argue that this is acceptable (and even preferable) because these 'spaces' are not part of our ex-ante conceptual vocabulary, unlike e.g. the theory-laden concepts of shielding, nurturing, empowering. Instead, these five spaces emerged from our reading of the empirical material as discursive categories used by PV actors. As such, these spaces are not rigid, immutable analytical categories to which data are mechanistically allocated and which provide "prescriptions of what to see"([19]:p. 148): they follow *from*, instead of are superimposed *on*, the empirical material. Although we considered conceptualizing 'policy'—a sixth category invoked by several PV actors at various times as influential for PV development—as a separate space, we chose instead to conceptualize policy as partially constituting, supporting and disrupting the other spaces rather than as a space in itself; not only because policy seems to play strong (but different) roles in each space, but more importantly because actors across the aforementioned spaces mobilize it as such: they draw upon policy (in the energy domain, but also other policy domains like housing) as a resource for constructing other spaces for material PV development.

This resulted in a descriptive case history of Dutch solar PV development in five different spaces which can be found in Section 3. This section describes who the key actors were and what work these actors did in each space. Internally, for each space, this is done chronologically. In this paper, the five spaces are ordered in such a way as to maintain chronology as much as possible (i.e. Section 3 starts with 'research and development' because the earliest 'key event' from the timeline took place in this particular space). Yet this is not always possible: in many instances, timelines overlap between spaces (i.e. the spaces are not consecutive but partially overlap in time), and so consecutive sections can 'jump back in time' to reflect the non-linearities of PV development across our spaces. The subsequent step—answering our main research question necessitates an analysis of protective space whose protocol is described in Section 2.2.

2.2. Protective space analysis

After the descriptive case history of Dutch solar PV in the five spaces, we explore the utility of the concepts of shielding, nurturing and empowering as proposed in [10] in understanding how PV advocates have managed to create and maintain spaces for PV action in The Netherlands. These three concepts are our vehicles for recontextualization: they are tentative candidates for 'generative structures' that transform the case history in Section 3 into a case *study* to answer the open-ended question about how solar PV technology has managed to survive in The Netherlands despite harsh policy and socio-economic contexts.

2.2.1. Shielding

Smith and Raven [10] argue that the function of shielding work is to stave off selection pressures from socio-technical regimes and provide room for experimentation. They differentiate between active and passive shielding. Active shielding is about the creation of protective spaces through targeted support for a specific innovation, while passive shielding is about the mobilization of pre-existing, non-targeted spaces that nevertheless provide some form of protective shield for the specific innovation of concern (to advocates). When examining the case history of Dutch solar PV development through the conceptual lens of shielding, we are thus interested in evidence of activities such as mobilizing pre-existing generic research subsidies for solar PV, locating solar PV experiments in favorable geographic locations in which selection pressures are different, creating subsidies or rule exemptions for solar PV, and tolerating/justifying its poor technical and/or economic performance (see: Table 1).

2.2.2. Nurturing

If shielding is about creating a protective space, then nurturing is about ensuring that this space is utilized. From an outsider perspective, the function of nurturing is thus to improve the socio-technical and/or economic performance of solar PV in these protective spaces so as to reduce its dependence on shielding. This function is the domain of 'classic' Strategic Niche Management, which has been developed as an ex-ante (policy) instrument for increasing a sustainable innovation experiments chance of success by optimizing learning strategies, networks and expectations [5].

2.2.3. Empowering

A sustainable innovation which has been shielded from mainstream selection pressures and successfully nurtured, can develop into a market niche when adapted to suits the needs of a particular (but small) market segment without requiring further support [20]. Strategic Niche Management explains these dynamics through networks, learning and expectations—processes which are reconceptualized in this paper as the 'nurturing' dimension of protective space. However, in order for a sustainable innovation to realize its 'path breaking' potential and instigate wider change *more* is required. How such 'niche-regime' interactions operate is still largely unknown in transition studies [21]. In response, Smith and Raven [10] have argued that in order for sustainable innovations to 'break through', innovations need to be *empowered.* Innovation champions engage not only in 'inward-oriented system building' within protective spaces, but also in 'outward-oriented' activities aimed at changing mainstream contexts. Smith and Raven [10] particularly emphasize the discursive practices of 'global networks' and distinguish

[2] A program manager at a regional development corporation; a project attendant at an energy company; a senior researcher at an environmental research institute; a CTO of a high-tech PV start-up; and a program director at a national energy research institute.

[3] In this particular case we could build upon previous academic interpretations of PV developments in the Netherlands to categorize the spaces (e.g. [18,46]) and cross-checked them with our own additional primary data sources. This led to the final characterization of the five spaces as mentioned here.

Table 1
Concepts, functions and indicators for analysis of protective space.

Conceptual lens	Description	Look for evidence of
Shielding	Stave off pressures from mainstream selection environments	mobilizing pre-existing generic support e.g. for research implementing the innovation in favorable (geographic) locations
	Create space for experimentation	creating financial support, temporary rule exemptions for innovation tolerating ‘poor’ economic/technological performance
Nurturing	Improve socio-technical/ economic performance of shielded innovation	broad and reflexive learning articulating specific and shared expectations building broad and deep networks
Empowering	Remove shielding: Innovation succeeds under conventional selection criteria (‘fit and conform’)	arguing and promoting that innovation will be competitive under conventional criteria arguing that no radical changes are required framing shielding as temporary framing nurturing as targeting performance improvement
	Institutionalize shielding: innovation changes conventional selection criteria (‘stretch and transform’)	arguing for and achieving institutional reforms framing shielding as manifestation of sustainable values framing nurturing as learning process towards sustainability

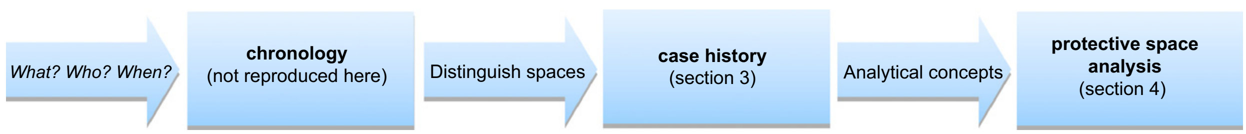

Fig. 1. Schematic methodology.

two different forms of empowering an innovation. ‘Fit and conform’ implies that, actors will emphasize that protection is only necessary temporarily, and that after shielding is removed, the innovation can successfully compete under mainstream selection pressures. Conversely, ‘stretch and transform’ implies that innovation champions will promote that shielding is not (fully) removed, but that parts of it become institutionalized: the innovation does not conform to, but instead *changes* conventional selection criteria (e.g. sustainability becoming a criterion in the evaluation of new innovations across the board). In either case, innovation champions will have to develop *narratives* that are acceptable and make sense to potential funders, decision makers and the like.

Consequently, when examining the case history of Dutch solar PV development through the conceptual lens of empowering, we are thus interested in work around ‘fit and conform’ and ‘stretch and transform’ logics (see: Table 1). Some tentative indicators for ‘fit and conform’ narratives are (a) claims that for the success of the innovation, no radical changes (e.g. in infrastructures or regulation) will be required, (b) claims that the innovation will be competitive under conventional selection criteria, (c) framings of ‘shielding’ measures as temporary, and (d) framing ‘nurturing’ measures as primarily targeting technical and/or economic performance improvements. Alternatively, some tentative indicators for ‘stretch and transform’ discourses are (a) claims that call for institutional/infrastructural reforms, (b) framings of ‘shielding’ measures as manifestations of sustainable values, and (c) framing ‘nurturing’ measures as learning processes towards sustainability (see: Table 1). Fig. 1 gives a schematic overview of the methodology presented in this section.

3. Case history: solar PV developments in five spaces

3.1. Space 1: research and development

In The Netherlands, solar PV emerged as a subject of interest for physicists and chemists already in the 1920s. E.g. crystallography professor Jaeger saw it as a possible solution for the depletion of natural resources in the context of rapid industrialization: “(…) eventually, when coal shortages arise and humanity’s existence is threatened by energy shortages, photo-chemistry could become its salvation” [22].

The study of photovoltaic phenomena subsequently found a foothold in research into the fundamental properties and characteristics of matter. In the 1930s, Dutch electronics manufacturer Philips did some PV research, but stopped because of efficiency and handling problems ([18]:p. 209). But by the 1950s, the invention of the transistor had improved the perspectives for semiconductor research. By the 1950s, solar PV secured its first practical application as a power source on satellites: in space, its high production cost was not an issue as few alternatives were available. In 1957, the Dutch Foundation for Fundamental Research on Matter (FOM) discussed a report about the state of Dutch PV research efforts, which was heavily criticized by most board members: nuclear power was considered to be the future of the Dutch energy system ([18]:p. 210). The discovery of large natural gas fields from the late 1950s onward and the subsequent fast roll-out of a gas infrastructure further decreased the urgency of (any) alternative energy sources.

In the early 1970s, the Dutch nuclear power project became contested, e.g. by the ‘Working Group Nuclear Power’ (WKE) which consisted of concerned scientists and ‘electricity regime insiders’ [23]. In 1972, WKE member, DaeyOuwens (of Eindhoven Polytechnic) wrote a project proposal entitled “Conversion of solar energy to electrical energy using semiconductors” ([18]:p. 211). DaeyOuwens, who had experimented with silicon PV cells at Philips in the late 1950s, saw potential for solar PV as an energy source if applied to unused large areas with high solar radiation incidence, such as deserts and the sea ([18]:p. 211). A 1973 symposium discussing the proposal was well-visited, in part because energy had become a major societal issue due to the 1973 oil embargo of OPEC countries ([18]:p. 48). The general impression was that the technology had great potential and could in the long run be the sole solution to the energy issue ([18]:p. 211). Political opponents of the nuclear power project suggested investing in solar PV [24], but the Minister of Economic Affairs, responsible for energy policy, considered it to have been “developed for space” and “unacceptably expensive” [25].

Nevertheless, the government became concerned about the risks of Dutch dependence on foreign fossil fuel and so, the National Steering Group Energy Research (LSEO) was established to set up research programs that would contribute to diversification of the Dutch energy supply ([18]:p. 58–59), a goal which was reiterated in the 1974 Memorandum on Energy [26]. Daey Ouwens was one of its members ([18]:p. 58). The LSEO's intermediate report contained recommendations on several alternative energy options. It subdivided 'solar energy' into (a) thermal, (b) conversion to other energy carriers (e.g. hydrogen), and (c) direct conversion to electricity (solar PV). The report remarked that solar PV discussion was dominated by the cost price issue, and was pessimistic about the viability of the Dutch development of PV cells given the substantial international research efforts. It nevertheless argued that an evaluation of solar PV, which would assume that this cost price would eventually come down as a result of investments abroad, was desirable. It argued that such a study should be focused on "energetically speaking smaller decentralized units (1–10 km^2)". *Very* small (decentralized) applications were not discussed at all. The study was to examine grid connection as well as battery-charging, and compare the "use of land for agriculture and for electricity production", which seems to assume that large PV power stations might be built on rural land. Another advantage of such a study, the report argued, would be that "should it become evident that application in The Netherlands is not realistic, but that it would be in sunnier countries such as Italy or Spain, The Netherlands could participate" [27].

Its second report [28] concluded that for the short term (before 1985) oil and gas would remain the dominant energy sources: dependency and depletion could only be countered in the short term by energy saving measures, which should therefore be thoroughly evaluated. Renewables in general would only play a role in the long term (after 2000), and because it was unclear which ones would be preferable, a broad spectrum of research was desirable. The conclusions were adopted by the government, which announced several national research programs into the various options: wind power (NOW), geothermal (NOA) and solar (NOZ) ([18]:p. 76). A working group was established to prepare for a National Research Program Solar Energy (NOZ-I). The working group consisted largely of members of KZK (Contact Group Solar Energy for Climate Control, an informal group of experts around solar thermal [29]) and ISES (the Dutch chapter of the academic research network 'International Solar Energy Society' ([18]:p. 184).

Its 1977 report focused exclusively on thermal applications of solar energy (e.g. passive and solar boilers), which were seen as the only economically viable applications of solar energy in the short-to-medium term. As such, NOZ-I started in 1978 with solar PV as only a miniscule part. As a result, by 1980, the Dutch PV research effort was small in comparison to its foreign counterparts. Because of the government's low expectations (and support) of solar PV for The Netherlands, its academic advocates reframed solar PV as an energy technology for developing countries—a prominent theme after the 1973 oil crisis. ISES also lobbied for an expansion of the Dutch PV research program with the Ministry of Education and Science (responsible for science and technology policy), which asked ISES to produce a concrete program proposal. In 1982, the report entitled 'A Sunny Future' argued for an expansion financed with NOZ funds, but by then the responsibility for science and technology policy was transferred to the Ministry of Economic Affairs which was not interested ([18]:p. 219). In 1982, the Energy Research Centre of The Netherlands (ECN) published a proposal in preparation for the second National Research Program Solar Energy (NOZ-II 1982–1985), which prioritized the technologies which would be commercially viable the soonest. This (still) meant thermal conversion: for The Netherlands, solar PV was still not believed to be suitable ([18]:p. 219). Few practical solar PV projects resulted from NOZ-II: many still considered PV to be a long-term option at best ([18]:p. 220).

This view was reiterated in the 1984 final report of the Broad Societal Discussion (BMD)—a large public debate in the early 1980s about Dutch energy policy that had been prompted by a nuclear power policymaking stand-off in the late 1970s. On solar PV, it concluded that "a contribution of any (quantitative) significance to electricity generation using *solar cells* is not to be expected in The Netherlands before the year 2000" ([30]:p. 300).

But by the mid-1980s several early PV advocates held influential positions as university professors with a direct line to the Ministry of Economic Affairs ([18]:p. 231). Their efforts, as well as the success of commercial projects abroad (see: Section 3.3) contributed to a shift in the Ministry of Economic Affairs expectations regarding solar PV in the mid-1980s [31]. When NOZ-II came to a close in 1985, the first research program dedicated exclusively to solar PV (NOZ PV 1986–1990) was established as distinct part of NOZ-III. Its concrete goal was to keep up with international PV developments [32] as well as investigate possible applications in developing countries and later in The Netherlands. The four-year program's budget was largely spent on new fundamental research (72%), but also on practical application (e.g. 13% for applied research into modules and systems).

By the end of NOZ PV, the government was more enthusiastic about solar PV. In 1990, the Dutch Organization for Energy and Environment (Novem), the Ministry of Economic Affairs energy agency, published a memorandum on energy conservation which stated that although solar PV was still too expensive for large-scale grid-connected systems, it could "(…) in principle become the most important renewable energy option after 2010" [2]. This was partially based on PV researchers' expectations that the price of PV electricity equal that of 'regular' electricity by 2010 because of expected efficiency improvements and production price drops. It also connected renewable energy sources such as PV with broader discourses and policies on climate change—a topic which had climbed the political agenda since the late 1980s.

The memorandum announced a follow-up to NOZ PV whose main focus would be on its embedding in the Dutch energy system through research, development and demonstration ([18]:p. 232). In NOZ PV-II (1990–1994), over 1/3 of the substantially increased budget was earmarked for modules and systems research. In terms of fundamental research conducted under NOZ PV-II, the focus shifted from 'first generation' monocrystalline to 'second generation' polycrystalline and amorphous silicon 'thin film' PV, and 'third generation' organic cells ([18]:p. 232).

Another shift in the 1990s was that from primary cell research to development and demonstration ([18]:p. 232). In the second half of the 1990s, solar PV formed the largest share of spending on research and implementation of renewable energy in The Netherlands ([18]:p. 235). Some researchers felt that market development was at that point more important than efficiency improvement ([18]:p. 234). This view was institutionalized in the follow-up NOZ PV 1997–2000 which was even more market-oriented: it sought to create conditions and remove barriers for large-scale implementation of solar cells in the Dutch electricity system [33]—referring to broader shifts in discourses and policies since the beginning of the 1990s decade on introducing competition into gas and electricity regimes (see Section 3.5).

Research institutes increasingly collaborated with (Dutch and foreign) partners from industry [33] and launched high-tech spin-offs companies in the late 1990s. In the late 2000s, research institutes ECN, Holst Center, TNO and Eindhoven University of Technology established Solliance as a collective initiative geared towards research into the production of thin film PV cells and

modules. In 2011 it presented a roadmap to the Minister of Economic Affairs, Agriculture and Innovation which emphasized the PV sector's large potential for job creation. But most of these PV jobs would not be realized in research, but in manufacturing and industry. The history of this second key space in Dutch PV development is described in the next section.

3.2. Space 2: PV industry

After the energy crisis, Dutch electrical engineering company Holec became interested in energy solutions and founded Holec Energy Systems. In 1979, it established Holecsol Components, the first Dutch PV factory [31] and in 1981 Holecsol Systems ([18]: p. 216). Trade organization Holland Solar was established in 1983 to both promote (mostly thermal) solar energy, and to represent the interest of its 15 members which included manufacturers, research institutes, consultants and installers (at that time mainly of solar boilers). Expectations were articulated about economies-of-scale and a large domestic market for solar PV which would form the basis for a solid export product. In 1984, Dutch multinational oil company Shell also entered the solar PV business, as many of its foreign competitors had done [34]. It established R&S Renewable Energy Systems BV which took over Holecsol Systems ([18]:p. 279) and much of Holecsol Components (whose manager became general manager of R&S). R&S started producing PV cells in Helmond in 1986 [31].

When grid-connected systems became increasingly important over the 1990s, photovoltaic inverters were required to convert the variable direct current output of a solar panel into a standard alternating current that could be fed into an electrical grid. Established companies catered to this demand, e.g. in 1993 electrotechnical firm Mastervolt launched an inverter that it had developed in collaboration with Shell Solar and Ecofys and subsequently developed into a global player in this field [35]. From the mid-1990s onward, capabilities from process engineering from other sectors spilled over into PV as established equipment manufacturers began to specialize on the production of equipment for the production of PV cells (e.g. Smit Ovens and Tempress, which closely collaborated with ECN). As PV manufacturing was an expensive process, production cost saving technologies also drew interest, e.g. ECN spinoff RGS Development which developed a process that reduced silicon material loss during wafer production. Another example is OTB, a company which had produced machinery for the production of dust-sensitive materials (e.g. lenses) without expensive cleanrooms since 1994, and was asked by Shell Solar Energy (which had been the new name for R&S since 1997) to develop similar machines for the industrial-scale production of PV cells in 1999.

Yet in 2002, Shell Solar Energy terminated its PV activities. Shell claimed the termination was part of a restructuring process aimed at making its solar energy division viable [36], but in 2006–2007 it quietly sold off most of its solar businesses [37] and announced its withdrawal from renewables in general more publicly in early 2009 [38]. In 2003, its former CEO founded Solland Solar for the production of PV cells. Another key new entrant was Scheuten Solar—set up in 2002 as a solar PV division of Dutch multinational glass producer Scheuten which made PV systems based on cells produced by Scheuten abroad [35].

PV industry actors increasingly framed solar PV as an interesting opportunity for building a new national high-tech industry. Comparable to the IT industry, in which The Netherlands substantially contributed to the market for microchip production machinery (e.g. ASML), Dutch firms increasingly competed internationally in the production and supply of the equipment necessary for the production of PV systems as well as the systems themselves. By 2008, some 30–40 small to medium-sized firms were active in the Dutch solar PV sector, with activities ranging from (equipment) supply to production and distribution, employing an estimated total of some 1200 people ([39]:p. 3). At that time, the sector's turnover had already quadrupled compared to 2004 and, profiting from fast-growing foreign markets such as in Germany with more favorable policies, exports of PV systems had risen substantially, as well (see Fig. 2).

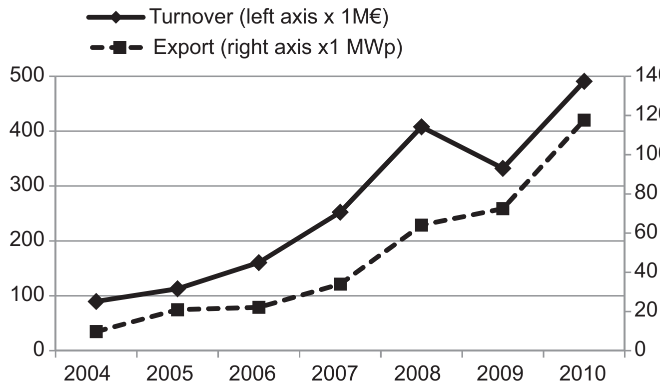

Fig. 2. Dutch PV industry turnover (black line, left axis, in M€) and PV systems export (dotted line, right axis, in MWp). Source: Netherlands Statistics (CBS).

In spite of these positive results, some actors in the Dutch PV industry felt that it was relatively invisible to the government [40]. While the 'raw material' for a high-tech PV industry existed in The Netherlands, expertise was distributed among many relatively small firms which had no common representative. To repair this, the Brabant Development Corporation (BOM) and ECN established the Solar Industry Platform (SIP) in 2011 to unite and represent many PV industry actors and lobby for their interests. Because Holland Solar represented the interests of both thermal and PV solar firms as well as installation companies, and Cleantech Holland (a technology industry platform established in 2008) encompassed multiple renewable technologies and focused on export, the sector welcomed this initiative [41]. Early SIP members included the aforementioned OTB Solar, Scheuten Solar, Solland Solar, Mastervolt, Smit Ovens and Tempress. It published a periodical entitled 'Solar Magazine' which was distributed among its members but importantly among politicians as well, in line with SIP's ambition to be an accessible and representative conversation partner for government in solar PV industry matters [40]—an audience which the industry perceived to be especially important for the industry's future. While the current focus is strongly on grid-connected systems (Section 3.4), the roots of commercially available PV systems lie with off-grid applications. The next section will describe the history of this space for such autonomous PV systems.

3.3. Space 3: autonomous PV systems

Early experiments with autonomous solar PV took place abroad and especially in rural areas which had no (reliable) grid connections and/or where solar incidence was far higher than in The Netherlands. For example, in the late 1970s, Dutch trade company Ceteco started selling water pumps powered by French solar cells in Cameroon, but switched to Holecsol's cells in the early 1980s ([18]:p. 351). Another example is the solar PV powered radio station ('Radio Hoyer') that went on-air on the Dutch island territory Curacao in 1984 [42]. The station wanted switch to the FM band for greater range, but this required a new facility on a mountain where grid connection was not available and prohibitively expensive. As such, a (fully commercial) system based on 128 solar panels was designed and constructed [43].

In the early 1980s, prominent Dutch PV advocates had also argued for solar PV as a means of rural electrification in the

former Dutch colony of Indonesia ([18]:p. 349). In 1988, some 80 unelectrified homes in the Indonesian village of Sukataniwere equipped with 'Solar Home Systems' which powered domestic and street lighting, radio communications equipment and a communal television using solar panels and a battery. It was a joint project between Shell's R&S and BPPT, the Indonesian agency for assessment and application of technology. Through the project, R&S wanted to learn about technical aspects but also social acceptance, in order to estimate whether large-scale rural electrification using this system was economically feasible ([18]: p. 350). The project was subsidized by the Dutch and Indonesian governments. In 1991, a follow-up project in Lebak (Indonesia) was initiated by PV pioneer Daey Ouwens and the Province of Noord-Holland and executed together with BPPT, Indonesian and local authorities [42]. The project was set up three stages with decreasing subsidies for purchase and installation: of the 2000 installed systems, 500 were unsubsidized ([18]:p. 353).

Autonomous PV experiments and demonstrations were undertaken in The Netherlands itself as well, although mostly in places that *did* have access to the electricity grid. Framing the projects as autonomous PV systems prevented these systems from being judged from the perspective of the existing centralized energy system, which would render them economically unfeasible. For example in 1983, Holecsol initiated a PV demonstration project that involved the installation of a solar PV system at a nautical school on the Dutch island of Terschelling [31]. It was subsidized by the Ministry of Economic Affairs as part of the NOZ-I program, and by the European Community as part of its European demonstration project for the development of new energy sources ([18]:p. 216). The autonomous system was the first large-scale PV project in Europe ([42]). The island was chosen because of it relatively high incidence of solar radiation as well as wind speeds [44]; some key technical lessons involved the effects of salt and UV on cabling [31].

A residential building was outfitted with an autonomous PV system for the first time in 1988 by R&S. The project was initiated by Daey Ouwens and the inhabitant of the end-of-terrace 'solar house' in Castricum. In 1989, the 'home of the future' opened in Rosmalen. This project was initiated by leisure park company Libema, building company Intervam and ChrietTitulaer (a popular technology trend watcher on Dutch public television). The 'home' was outfitted with an R&S PV system and was subsidized by the Ministries of VROM and Economic Affairs through its energy research agency Novem, which used the house to display its activities [45].

One of the earliest *commercial* applications of autonomous Dutch solar PV in The Netherlands was as a cheaper-than-gas power source for lights on buoys and beacons. These were produced by companies such as Stromag [42]. Over the 1990s, autonomous solar PV was also commercially applied on recreational vessels and houseboats ([18]:p. 233). More recently, street lighting, remote measuring stations and parking meters were outfitted with solar PV-fed batteries [31]. In the small and densely grid-connected Netherlands, this was a relatively small market: though growth was steady, it was slow and in the mid to late 1990s, it was overtaken by grid-connected PV in terms of installed capacity. This was to a large extent the consequence of demonstration and market creation projects involving grid-connected PV systems integrated in new buildings. The next section will detail the history of this building-integrated solar PV space.

3.4. Space 4: building-integrated PV

In late 1989, a grid-connected PV system was successfully tested on a (non-residential) test house on the Energy Research Centre of The Netherlands (ECN) grounds, which showed that grid-connected PV was technologically feasible in The Netherlands. Other projects were small building-integrated PV tests between 1991 and 1994 in Heerhugowaard (10 houses) and Woubrugge, Lekkerkerk and Zandvoort (one house each). But academic studies argued that although technologically feasible, PV was not yet market-ready: available PV systems were not yet tailored to housing development, they suffered from prohibitively high prices, and construction industry actors (architects, project developers) had little experience with them ([46]:p. 1). Supporting demonstrations projects was thought to solve these issues and prepare PV for market introduction. The market segment of 'grid-connected, decentralized, integrated PV systems in new housing' was singled out for support, on the grounds that supporting a single 'product-market-combination' (PMC) the most cost-effective way to allocate the budget ([46]:p. 6). The government chose this option for several reasons (see: Table 2).

When the government's focus for PV support turned to market creation and the NOZ PV budget increased substantially in the second half of the 1990s, dozens more building-integrated PV projects were initiated, totaling many hundreds of houses, e.g. the Amersfoort 1 MW project which consisted of some 500 houses [46]. These projects' emphasis was primarily on technical learning, e.g. about inverters and achieving common standards between PV module manufacturers and construction industry. Learning about user preferences and practices was not a key strategy: inhabitants received (and could provide) little feedback and societal embedding was not a key goal [47]. In 1997, on the initiative of the PV industry and the energy sector, a voluntary covenant was made between virtually all players in the PV field (including the Ministry of Economic Affairs, large contractors, energy companies, solar cell and panel developers and producers) that aimed to increase the installed capacity of solar PV to 10 MWp by the year 2000 in order to create a substantial domestic market for PV. From that time onward, people also began to equip *existing* buildings with off-the-shelf PV systems which were starting to appear on the market. The next section describes the history of this space for retrofitting solar PV.

3.5. Space 5: retrofitting PV

In 1995, energy company PNEM began marketing 'green electricity'; an initiative that proved successful in spite of higher prices. A 1999 campaign by the Ministry of Economic Affairs and the World Wildlife Fund promoted switching to green electricity by framing it as a means of combating climate change. This was supported by financial measures (e.g. a tax exemption on the consumption of green electricity) which rendered the price difference between green and 'gray' electricity effectively zero for consumers. This resulted in a large green electricity customer base already at the turn of the century. However, their demand was mostly met through importing green electricity: it did not result in substantial new domestic green electricity capacity [48]. 'Green electricity' was also a prominent aspect of profound changes in the organization of the Dutch electricity sector which were unfolding at the time. In accordance with European guidelines aimed at the formation of a common European energy market, the Electricity Bill of 1998 announced a stepwise liberalization of the Dutch electricity sector. The introduction of market forces was thought to reduce prices and increase quality of service, as well as stimulate the use of renewable energy. Anticipating the complete liberalization in 2004, electricity companies used green electricity (the market for which would already be opened on 2001) as a marketing tool to retain existing customers and attract new ones [48]. Their advertising campaigns, in combination with attractive prices, resulted in high consumer interest in green electricity [49]. In this context, energy companies Nuon and ENW, together with Greenpeace, initiated the Solaris project in 1999. This project offered Nuon's customers

Table 2
PMC characteristics and considerations ([46]:p. 7).

characteristic	Considerations
Grid-connected	• contribution to renewable energy supply • grid as buffer
Decentralized	• large possible area • cost-effective sooner than PV plants (e.g. less transport loss with supply-side production)
Housing	• accessible market segment • interesting segment for energy companies • no relevant learning experiences abroad with PV housing development
Integrated	• long-term cost savings though material saving • more a esthetically pleasing than later additions
New construction	• involving entire production and marketing chain • large potential (because of substantial long-term housing development plans)

the option of purchasing commercial, off-the-shelf PV systems at a reduced price of about half the going rate [50]. The project was financed by the Ministry of Economic Affairs' energy agency SenterNovem ([39]:p. 17). Several thousand PV systems were sold through this project, which from the perspective of SenterNovem was aimed at creating a market for solar PV. Nuon participated to realize its renewable energy targets, diversify its product portfolio and 'bind' its existing clients [51]—with an eye on the upcoming opening-up of the green electricity market for consumers in 2001.

As of that year, the Implementation Scheme Energy Subsidies EPR (a subsidy instrument established in 2000 that partially compensated consumers for their purchase of energy saving measures and appliances based on a new European system of energy labels) also compensated the purchase of solar PV systems. The EPR subsidy budget was determined annually and paid for out of revenues of the Regulatory Energy Tax (REB) on the use of electricity, from which 'green electricity' had been made exempt in 1998 [52]. This boosted sales of solar PV systems substantially (see Fig. 3), which dropped after the EPR was abruptly ended in late 2003 by a new center-right coalition that severely cut green electricity subsidies [53].

The new government clearly did not view solar PV as a viable option for domestic energy production: in response to Labor proposal to reinitiate subsidies for solar PV, the Ministry of Economic Affairs replied that "if The Netherlands were located in the Sahara, then solar PV would be an extraordinarily interesting option" [54].

When a new center-left government came to power in 2006, new measures to stimulate a domestic market for PV were announced. In its 2007 coalition agreement, the new government promised to stimulate consumers' investments in improving the energy efficiency of existing housing [55]. In early 2008, a subsidy on *use* of solar panels was announced, as opposed to the EPR which had subsidized purchase (although municipal subsidies on purchase remained available in some cities). It became part of the Ministry of Economic Affairs' broad Stimulus Policy Renewable Energy Production (SDE) [56]. While the SDE's main focus (and largest budget) was for wind power and biomass, it also claimed to want to pave the way for a large-scale roll-out of solar PV [57].

The SDE targeted both private individuals and businesses, subsidizing the production of green electricity per unit supplied to the grid, using a different amount for each renewable source. This amount was calculated as the difference between the average electricity price for consumers and the estimated cost of producing a kWh with a specific renewable option [58], so that the subsidy would e.g. decrease as renewable electricity production became cheaper and/or fossil fuel prices increased. The price points would be assessed and amended annually. The measure proved (too) popular especially for solar PV and the budget was quickly depleted. In 2009, the government decided to shift unclaimed subsidies for other sources to solar PV and only marginally adjusted the 'rules' in 2010. The number of applications far exceeded the allotted maximum in every round. However, the rules for the 2011 SDE round were drastically changed by a new center-right government that had come into office in 2010. Instead of differentiated cost-of-production estimates for different renewable sources, a single amount was set for all renewables which for solar PV meant a drastic reduction. Additionally, subsidies for small PV systems (<15 kWp) were terminated altogether [59]. Without subsidies on either purchase or use, solar PV system sales stagnated again. In response, various initiatives looked for other ways make solar PV accessible for consumers through new business models [60,61]. A few such models are listed in Table 3.

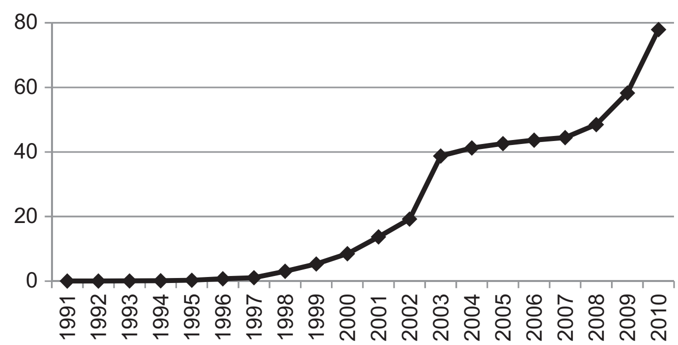

Fig. 3. Cumulative sales of grid-connected PV system sales to installers and end users (in MWp). Source: Netherlands Statistics (CBS).

3.6. Summary

The preceding section has reconstructed the history of Dutch solar PV in five spaces. The descriptions yielded a picture of a long, winding and open-ended innovation process, during which PV advocates have engaged in system building activities in an often unfavorable (and virtually consistently uncertain) environment, variously constrained and enabled by erratic government policy. In the next section, we make a protective space analysis: we apply the concepts of shielding, nurturing and empowering to see to what extent they can explain the survival of solar PV in The Netherlands.

4. Protective space analysis: shielding, nurturing, empowering

This section explores to what extent the framework articulated by Smith and Raven [10] makes sense for understanding the process of (a) constructing, (b) maintaining and (c) removing,

Table 3
Examples of business models for solar PV after 2010.

Business model	Example	Details
Collective purchase of solar PV systems	Foundation WijWillen Zon ('We Want Sun')—initiative of sustainability platform Urgenda	Negotiated volume discount with Chinese PV producer: world's largest collective purchase of solar panels by private individuals who, in spite of the absence of subsidies on use, can still use net-metering (i.e. only paying for the net amount of electricity drawn from the grid)
Leasing solar PV systems	ZonVast ('Fixed Sun') scheme—initiative of energy company GreenChoice	Solar PV systems are purchased, installed, maintained and owned by electricity supplier. Consumers pay for produced electricity at a flat fee which is set for 20 years. Requires ownership of roof
Solar PV cooperatives	Association Zon Op Nederland ('Sun on The Netherlands')—umbrella organization for local coops	Establishes and supports local solar coops - small groups of private individuals that collectively buy large solar PV systems and install these on adequately large roofs in their neighborhood (e.g. gym, barn) either rented, or owned by a participant

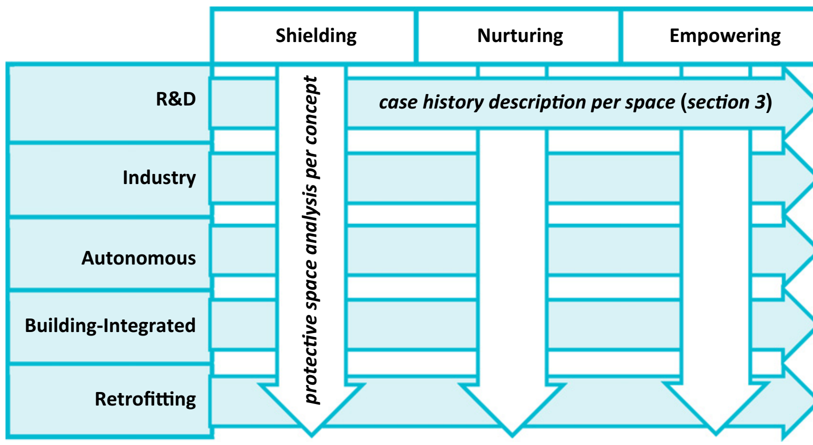

Fig. 4. Descriptive and analytical 'cross sections' of the Dutch PV case. Table 4 gives concrete examples located at the various intersections of the arrows.

institutionalizing or transforming protective space. We explore the utility of these 'meta-language' concepts by superimposing them on—and cutting across—the five spaces (see: Fig. 4).

We examined the case history for indicators of actor's shielding, nurturing and empowering activities by using as our lenses the 'prescriptions of what to see' ([19]:p. 148) listed in Table 1. Accordingly, Section 4.1 lays out our analysis of shielding, and Sections 4.2 and 4.3 do the same for nurturing and empowering. By way of illustration, we also provide a matrix (Table 4) which contains some examples of what we perceived as shielding, nurturing and empowering work in each space (please note this table is not comprehensive).

4.1. Shielding

Shielding is about solar PV advocates attempting to prevent 'their' technology's 'premature death' due to mismatches with existing socio-technical configurations. In involves activities aimed at exempting solar PV from various main stream selection pressures, such as those emanating from the fossil-fuel based electricity production regime.

When we look at Dutch PV developments in the various spaces through a 'shielding lens', we see that across the spaces, shielding is brought about through heterogeneous work, including mobilizing pre-existing financial resources, tapping into generic subsidies, lobbying for specific ones, and choosing favorable geographic locations for projects. We see that across the spaces, actors have consistently been able to shield solar PV from regime pressures by creating new—and mobilizing existing—protective spaces.

We found the earliest shielding activities in the research and development space, where shielding consisted of the mobilization of funds for applied semiconductor research in corporate research labs for concrete industrial purposes (e.g. for the space industry). But after growing concerns about fossil fuel depletion and environmental pollution of the early 1970s, solar PV was framed by several few university researchers as an alternative (terrestrial) electricity generation option. Because the first national solar energy research program focused exclusively on solar *thermal* energy, these researchers shielded PV by mobilizing university funds earmarked for materials research and by engaging in lobbying. They framed autonomous PV as a particularly attractive option especially in unelectrified regions of developing countries (because it would increase quality of life) and initiated several projects there. These projects, together with geographic locations in The Netherlands with electricity demand but no grid access (e.g. recreational vessels, buoys), provided a very small but persistent protective space for autonomous PV systems. In turn, this shielded the early Dutch manufacturing of PV cells (by providing a small niche market).

The work on these projects itself, while typically seen as nurturing work, can also be construed as a type of shielding work: it contributed to the government's perception of PV as a possible future energy option in The Netherlands and, via dedicated funding, to the domestic building-integrated PV projects of the 1990s which were in part aimed at creating a substantial domestic market. But the governments' withdrawal in the early 2000s from the 1997 covenant and abandonment of PV as a short-term renewable energy option for The Netherlands resulted in a failure to achieve significant domestic demand, which eroded this particular protective space. In response, the Dutch PV industry increasingly focused on export of PV cells as well as of PV production equipment: doing so shielded Dutch PV from the lack of domestic demand by tapping into a growing international market (e.g. as a result of German PV policy).

Tax incentives for green energy technologies (e.g. the EIA) also shielded PV, as they were mobilized by businesses retrofitting

Table 4
Examples of shielding, nurturing and empowering across five spaces of PV development.

	Shielding	Nurturing	Empowering
Research&development	Corporate research labs: funds for applied semiconductor research University material properties research National solar energy research program (NOZ)	Gradual emergence of academic /industrial network ('open innovation') Expectations around cost reduction, efficiency gains and employment 'Learning by searching' yielded efficiency increases & new PV types	PV researchers' expectations about cost price drops institutionalized in research programs (e.g. In 1990 government declares PV 'most important future renewable energy source')
PV Industry	Small-scale PV experiments in developing regions supplied by Dutch PV industry Growing international market: focusing on export shielded industry from lack of domestic demand	1980s: small network of producers with expectations around economies-of-scale, domestic market, & export Emergence of trade organizations to act as industry representatives and facilitate knowledge exchange 'Learning by searching': manufacturing knowledge, but highly distributed	Comparison with Dutch success in international market for microchip production machinery links PV to 'high tech industry' discourse Manufacturers' claims about PV as mainstream construction material (enabled by standardization to fit with construction sector standards)
Autonomous PV systems	Unelectrified locations in Indonesia and Curacao Domestic experiments (Terschelling, Castricum) Small standalone applications (e.g. buoys, recreational vessels)	Expectations about potential for PV in developing countries Emergence of commercial actors & specialized firms supply (e.g. selling PV water pump systems or buoys) 'Learning by doing' in autonomous experiments yielded technical lessons (e.g. about effects of salt & UV)	PV argued to be economically competitive for locations where grid connection is unfeasible ('fit and conform' discourse) Success of projects in developing countries contributed to Ministry of Economic Affair's attitude change toward PV
Building-integrated PV	Dedicated NOZ PV programs (1904–2000) for experiments with building-integrated PV	'Learning by in doing' in building-integrated experiments yielded e.g. standardization 1997 covenant between governments and most actors in PV sector Expectations about a substantial domestic market	Popularity (and tax exempt status) of 'green electricity' Uptake of environmental values in government energy policy NOZ 1997–2000 to 'remove barriers for large-scale PV implementation'
Retrofitting PV	EIA: retrofitting commercial structures with PV tax deductible for businesses EPR+municipalities' subsidizing consumers' purchase of PV SDE: subsidizing *use* of PV the production New business models (collective purchasing, leasing etc.)	Retrofitting supported by a network of trade associations, environmental organizations and energy companies Emergence of installation companies for 'off the shelf' PV systems 'Learning by using' and 'learning by interacting' (e.g. internet forums) yielded knowledge about e.g. installation techniques among self-installers	Incorporating sustainability criteria in the tax system (e.g. EPR financed by revenues from tax on non-renewable energy sources) No permission required for placement of solar panels on roofs and walls Framing SDE measures as temporary (i.e. only subsidizing the difference in price between green and gray electricity, coupled with the expectation that the latter would inevitably increase)

commercial buildings with PV. Later, the EPR scheme shielded PV by subsidizing consumers' purchase of off-the-shelf systems. However, this scheme was terminated in 2003. Shielding of PV through subsidy programs was largely absent until the 2008 SDE package for various renewable energy options, which shifted the focus from purchase to use: it subsidized the production cost difference per kWh between a given renewable technology and 'regular' electricity (i.e. different amounts for different technologies). Subsidies on purchase remained available in some municipalities. SDE proved popular especially for solar PV and as a result, unclaimed funds for other sources were redirected, providing additional shielding. In 2011, the SDE was drastically changed (lower kWh fee, no subsidy for small systems). In response, actors looked for other ways to shield solar PV in spite of the absence of subsidies for consumers, which inspired a variety of business models, such as collective purchasing, leasing, solar coops etc.

4.2. Nurturing

Nurturing is about solar PV champions' work geared towards improving the sociotechnical and/or economic performance of the innovation—in other words, about ensuring that something useful happens *inside* aforementioned protective spaces. When we look at the developments in the various spaces through a 'nurturing lens', we see that across the five spaces, actors have engaged in various system building activities.

4.2.1. Actor networks

Mobilizing and constructing shields against mainstream selection pressures goes hand in hand with the establishment of new actor networks—a key strategy in nurturing radical sustainable innovation [9]. In response to 1970s energy crisis, Eindhoven Polytechnic employee Daey Ouwens and his colleagues e.g. at Utrecht University, had been key PV champions by initiating a small network of academic researchers interested in alternative energy sources. This network gradually expanded and exchanged information with colleagues abroad as well as outside academia. A small number of specialized firms emerged that supplied solar panels for off-grid projects in the early 1980s, and by the mid-1980s, a small network of Dutch PV manufacturers existed. Gradually, the network grew and the sector organized itself in trade organizations which represented the interests of both solar thermal and solar PV producers as well as installation companies.

Key network actors attained influential positions at research institutes and lobbied with the Ministry of Economic Affairs over the 1980s, which contributed to a change in the Ministry's attitude towards solar PV in the late 1980s. This resulted in a series of national solar PV research programs that, next to an

important ‘fundamental research’ component, also had a ‘practical implementation’ component. The available public resources and resulting projects in turn enabled the heterogeneous network of PV actors to grow over the 1990s. In 1997, this culminated in an extended heterogeneous network consisting of the Ministry of Economic Affairs, large contractors, energy companies, solar cell and panel developers and producers agreeing on a PV covenant. In spite of the Ministry’s abandonment of this covenant in the early 2000s (due to its re-prioritization of biomass and wind over solar PV in relation to the Kyoto protocol), PV was still supported by a network of trade associations (Holland Solar, DE Koepel), environmental organizations (Greenpeace, WWF) and energy companies (Eneco, Nuon). As a result of the popularity of the EPR (2003) and SDE (2008) schemes aimed at the stimulation of sustainable energy, PV installation companies sprang up.

In the R&D space, research institutes established a collective initiative geared towards research into the production of thin film PV cells and modules in the late 2000s. It pursued an ‘open innovation’ model, whereby interested parties were free to join the project as it proceeded. By that time, the failure to create a substantial domestic market had negatively impacted the Dutch PV industry (e.g. Shell terminating its solar PV production facility). Yet solar PV production expertise was fragmented rather than absent: it was simply distributed among many relatively small firms. For this reason, a solar PV industry platform was established in 2011 to unite and represent these actors and actively lobby in an attempt to create awareness in policy circles of the substantial size (and turnover) of the Dutch PV manufacturing industry.

4.2.2. Expectations

Expectations are a second key nurturing strategy, because actors use them to attract resources, build legitimacy and reduce uncertainties [62]. Macro-level (visionary) expectations about PV as humanity’s salvation in a post-coal world date back to the 1920s, but the first practical work on PV in the 1950s was guided by more concrete micro-expectations regarding industrial applications, which focused search activities on the properties and applications of crystalline silicon. In response to the oil crisis, increasing environmental awareness, and nuclear power expansion plans of the early 1970s, a small network of researchers articulated meso-level (functional) expectations about PV as an alternative electricity source. This implied however that PV would have to compete with the fossil fuel based electricity generation regime on ‘mainstream’ criteria such as price per kWh, which it could not. This resulted in the articulation of micro-level (performance) expectations which centered on future cost reductions and increases in efficiency, but these were not taken over by the government. Over the 1970s, academics thus coupled the idea that the economics of PV would be more favorable in locations with more sunshine to an extant development aid discourse, which resulted in meso-level expectations regarding the potential for autonomous PV in developing countries. Businesses picked up on this: e.g. commercial enterprises introduced PV water pump systems in Africa in the late 1970s. Dutch firms and researchers successfully cooperated on several autonomous projects in developing countries as well as engaged in domestic grid-connected experiments. These successes contributed to the meso-level expectation around solar PV as a potential future energy source in The Netherlands becoming shared (and reproduced) by the Ministry of Economic Affairs in the late 1980s.

In the early 1990s, expectations were highest for grid-connected, decentralized, integrated PV systems in new housing. Micro-level expectations were articulated around the electricity grid acting as a buffer for solving supply/demand discrepancies, around decentralized PV minimizing transport losses, around integrated PV having esthetic and material-saving merits, around housing as an accessible and interesting market for energy suppliers, and around new construction as having a large potential (in terms of number of houses) and involving the entire production chain. For these reasons, this specific product-marked combination which was singled out for policy support as the most cost-effective way to allocate the budget, guided by a meso-level expectation around economies-of-scale and creating a large domestic market. Such a domestic market seemed within reach in the late 1990s (e.g. participants in the 1997 covenant had articulated the goal of increasing the installed capacity of solar PV to 10 MWp by the year 2000).

But when the government withdrew its support for solar PV in the early 2000s, based on the expectation that biomass and wind would be more-cost effective ways to realize Kyoto emission targets in the short term, this meso-level expectation about a domestic market collapsed. Over the 2000s, the remaining Dutch solar PV industry actors articulated new expectations about the PV as a high-tech export product based in part on Dutch successes in the export in PV production equipment. Recently, PV advocates strategically connected these expectations with expectations regarding employment (e.g. Soilliance stating that in Noord-Brabant alone, some 25,000 solar PV jobs could be realized by 2020). On the policy level, expectations about solar PV shifted frequently over the decade and with the political color of the various cabinets (e.g. in 2008, after years without government financial support, the center-left coalition in articulated the expectation that PV would be a long term option for The Netherlands and thus framed the SDE support measures as ‘preparing PV for a long term roll-out’, while this support was withdrawn by the central-right government which came to power in 2010 and favored expansion of the nuclear power program).

4.2.3. Learning

Learning on multiple dimensions and by questioning underlying assumptions (second-order learning) is the third key nurturing strategy in building strategic niches [9]. This usually means a practice-based and interactive learning style.

Between the first interest in solar PV in the 1920s and the late 1970s, learning around solar PV was almost exclusively learning by searching [63]: fundamental research into the properties and characteristics of (primarily) crystalline silicon taking place in (first) corporate R&D departments and (later) university laboratories. This type of learning resulted in a large jump in lab scale efficiency of silicon cells during the 1950s, mostly achieved by research abroad. Learning by searching also resulted in new types of PV cells since the 1970s (CIGS, CdTe, amorphous Si), which saw gradual lab-scale performance improvements of these but did not result in a convergence on a dominant design.

Dutch researchers first engaged in practice-based learning outside laboratories in the 1950s when practical modules were first tested and manufactured. Practical efficiency was far lower than lab-scale but had gradually improved by the early 1980s, and then somewhat quicker by 2000 [64]. Learning was key to the Dutch PV manufactures in the early 1980s acquisition of production know-how, and expanded as the PV sector grew over the 1990s and yielded e.g. innovative methods for PV cell production (e.g. methods to minimize silicon loss in wafer cutting). Over the 2000s, as domestic production of PV systems gradually disappeared, learning shifted to skills regarding the production of PV system *production* equipment.

In the early 1980s onward practice-based learning in various autonomous PV projects (domestically and abroad) yielded technical lessons (e.g. effect of salt and UV on cables) as well as social lessons (e.g. effect on user practices in developing countries).

Grid-connected experiments in The Netherlands yielded technical lessons about the problems involved in connecting decentralized solar PV systems to the electricity grid (e.g. the need for a new type of inverter). Furthermore, practice-based learning was a key element of the building-integrated projects of the 1990s, but mostly involved learning about e.g. standards mismatches between the construction and the PV sectors, and not about e.g. about user preferences. Learning also took place in energy companies (e.g. Nuon's participation in the 1999 Solaris project) and was geared towards learning about distribution of solar PV and the role energy companies could play in decentralized electricity production in a liberalized market.

Interactive learning was thus limited in these projects, but became more prominent with the rising popularity of retrofitting PV. As the retrofit systems were 'off the shelf', many self-installers organized in user groups and exchanged installation, monitoring and maintenance techniques as well as knowledge pertaining to applying for subsidy and regulatory barriers (in recent years prominently using the internet). The market for retrofitting did not facilitate learning by using on the producers' side however, as most panels were foreign-produced (notably in China).

4.3. Empowering

An important element in empowerment is the articulation (and eventually, institutionalization) of empowering discourses [10,65]. When we look at the developments in the various spaces through an 'empowering' lens (Table 1), we see that across the five spaces, actors have articulated mostly 'fit and conform' discourses and implemented mostly 'fit and conform' strategies. But more recently, and in response to changing socio-political contexts, 'stretch and transform' discourses about solar PV have also emerged. Whether or not empowerment is successful depends on whether these discourses are institutionalized and lead to rule changes in the regime.

4.4. Fit and conform

'Fit and conform' empowerment is aimed at enabling solar PV to successfully compete with mainstream electricity generation technologies after shielding is removed, and eventually substituting these without radical changes in the socio-technical network of institutions, practices and infrastructures. Fit and conform discourses are discourses that argue for this strategy.

Empowering PV in 1970s followed a 'fit and conform' strategy. For example, the 1975 LSEO report only spoke of large-scale centralized application of PV in The Netherlands—the dominant paradigm for electricity generation in The Netherlands. PV was compared to other energy options on their terms and failed the comparison on price. As a result, PV champions looked for application domains where the disadvantages of PV were less important that its advantages. Especially in regions of the developing world, where grid connection was either impossible or prohibitively expensive but electrification provided many benefits in terms of quality of life improvement, PV was argued to be both economically and technically viable. This, too, can be seen as 'fit and conform' empowerment however: dominant selection criteria (price, performance) would be used for evaluating success, and PV would act as an autonomous substitute for e.g. diesel generators. The successes of these projects empowered PV in the sense that they contributed to positive change in Ministry of Economic Affair's perception of solar PV in the late 1980s. Increasingly, PV was framed as a domestic alternative to fossil fuel based electricity generation, as well. PV researchers articulated a fit-and-conform discourse about price drops and efficiency improvements leading to PV power being on par with regular power price-wise by 2010. This discourse was taken over by the government in 1990, which articulated that PV would likely become the most important renewable energy source after 2010. In the subsequent building-integrated experiments, PV manufacturers' attempts at standardizing PV modules to fit (literally) with construction sector standards, are also indicative of a fit and conform strategy: a way to enable wider diffusion of PV as a mainstream construction material. In the industry space, we see little evidence of empowering work before the early 2000s, when industry actors began comparing PV production to the Dutch success story of achieving a dominant position in the international market for microchip production machinery. This can be seen as an attempt at empowering Dutch solar PV industry by linking it up to a 'high tech export product' discourse, in response to the failure in creating a substantial domestic market as well as the withdrawal of government support for PV (in favor of biomass and wind) around the turn of the century. This discourse has 'fit and conform' characteristics: it frames PV as 'a marketable product like any other'.

4.5. Stretch and transform

'Stretch and transform' empowerment aims *not* at fully removing shielding, but rather at institutionalizing parts of it: it seeks to change mainstream selection by incorporating sustainability values. The power to change mainstream selection criteria lies largely outside the sphere of influence of niche actors [10], residing with historically more powerful regime actors. PV champions have to connect their PV discourses with broader discursive processes in society. If successful, altering a sustainable innovation's selection environment creates a feedback loop between market selection and sustainable innovations, with the former shaping the latter and vice versa through causing a shift in what characteristics are being selected for which is argued to enable more radical and profound sustainability transitions. Stretch and transform discourses are discourses that argue for this strategy.

We see the first indicators for stretch and transform empowerment of solar PV in the mid to late 1990s, when in 1995 several energy companies began marketing 'green electricity' and when in 1998 the consumption of green electricity received a tax exemption. The government's support of 'environmental values' can be seen as stretch and transform empowerment of green electricity in general: an attempt at transforming the selection environment in favor of sustainable energy production. Stretch and transform empowerment specifically for solar PV came in the form of NOZ 1997–2000: much more market-oriented than its predecessors, it sought to create conditions and remove barriers for large-scale implementation of decentralized (i.e. radically different from the regime) electricity production in the form of building-integrated solar PV.

The Ministry of Economic Affair's EPR measures for renewable technologies in the early 2000s can also be seen as stretch and transform empowerment: they were financed by revenues from a regulatory energy tax (REB) on non-renewable energy sources and thus leveled the playing field by incorporating sustainability criteria in the tax system. The EPR measures led to a run on off-the-shelf PV systems which consumers could retrofit without asking permission for placement on roofs and walls, in spite of The Netherlands' usually very strict procedures for alterations to existing buildings. Because it aimed at removing a regulatory barrier for the large-scale roll-out of solar PV, this also constitutes stretch and transform empowerment. The more recent SDE also had stretch-and-transform characteristics: because the subsidy pertained to gross production, no financial difference existed for consumers between 'using up' the electricity they produced and supplying it to the grid (which empowered decentralized

electricity production). The idea was that if average electricity prices would increase (i.e. because of fossil fuel shortages), the subsidy on PV would automatically decrease because the cost difference for the two modes of production would decrease. This was argued to ensure first a level playing field, and eventually a distinct advantage, for renewable technologies in general. But in spite of the EPR and SDE measures' stretch and transform characteristics, they ultimately also pursued a (conflicting) fit and conform strategy: they had fixed and predetermined budgets which practice prevented a large-scale roll-out of PV and a substantial domestic market.

In sum, Table 4 gives examples of shielding, nurturing and empowerment in the five spaces. In the final section of this paper we will draw conclusions.

5. Discussion and conclusions

This paper asked the question how PV was able to survive in the Netherlands despite, at times, very harsh policy environments. Indeed, our analysis has shown how PV advocates had to navigate many ups and downs in policy support. Moreover, we were interested in the usefulness of a recent framework proposed by Smith and Raven [10] that proposes to broaden analysis of emerging socio-technical systems from focusing on processes of nurturing within protective spaces to also include processes of creating and maintaining those spaces in the first place (shielding), as well as process of institutionalizing them by e.g. linking protective spaces to wider discourses in society and policy (empowering). We can now draw the following conclusions.

First, drawing upon primary and secondary data sources, this paper developed a case history of Dutch solar PV in five relevant spaces and discussed developments in each of these. These spaces have been defined as actor-categories: they are sites of action identified by actors themselves as important places were innovative action took place, partially shielded from mainstream selection pressures embedded in fossil-fuel based centralized electricity production. This constitutes a new angle on the history of Dutch solar PV which does not bestow explanatory power to aggregate social concepts. Rather, it emphasizes the strategic and navigational work that PV advocates undertake to claim a space for PV innovation, such as mobilizing pre-existing financial resources, tapping into generic subsidies, lobbying for targeted support, and choosing favorable geographic locations for projects.

Second, in terms of nurturing, our protective space analysis shows that that across the five spaces, actors have created and maintained heterogeneous actor networks; articulated expectations on micro- (e.g. about future performance and characteristics of PV), meso- (e.g. about the functions of solar PV), and macro-(e.g. about a post-carbon society) levels; and at various times engaged in learning processes including fundamental research on performance characteristics, generating know-how for PV cell and system manufacturing, contributing to processes of standardization resulting from building-integrated PV projects and interacting with end-users and exchanging retrofitting techniques. Thus, actors have engaged in socio-technical system building.

Third, in terms of empowering, our protective space analysis shows that actors have articulated mostly 'fit and conform' discourses about how the large scale implementation of solar PV does not require radical changes to existing socio-technical configurations. However more recently, and in response to changing socio-political contexts (such as a generalized perception of the urgency of climate change), actors have also articulated 'stretch and transform' discourses about how the selection environment should be altered to include sustainability criteria favorable to solar PV. While from an 'outsider' (system-level) perspective, such claims—if they are institutionalized—may enable a more radical sustainability transition, from an 'insider' perspective they may still be geared primarily towards advancing these actors' own (technology-level) interests [66]. Moreover, instead of being distinct processes, stretch-and-transform and fit-and-conform empowerment play out simultaneously. The picture is always confused and contradictory, as actors represent PV differently to different audiences on different grounds. Fit and conform help can elevate support for the technology, whose more radical social reconfiguration could eventually also stretch and transform power systems.

Fourth, these processes of shielding, nurturing and empowerment are not prescriptive 'silver bullets' for enabling sustainability transitions. In fact, what our study of PV in unfavorable contexts highlights is that PV innovation has not been a rational or consensual process of strategic niche building. PV advocates not only had to engage in system building, which in itself was full of negotiation over which PV innovation pathways to prioritize, but they also had to engage with broader regimes for energy generation, construction, third-world development work, and so on. Although these types of work have not all been highlighted equally in this study, we have broadly shown that PV advocates had to mobilize or construct protective spaces as well as work on (contributing to) changing broader contexts and strategically inserting their narratives into societal developments around market liberalizations, clean energy discourses, employment, developmental work, climate change and so on. In times of supportive policy environments, such as in the late 1990s, jumps were made in progressing PV innovation through effective nurturing programs, but at other times (such as in the 1970s or late 2010s) advocates were undertaking difficult and strategic work to mobilize and construct protective spaces or making attempts to reconfigure existing selection environments. This gives the impression of a piecemeal type of strategy, in which advocates at times had to take whatever protections were at hand, while at other times their strategies become increasingly intertwined with broader change processes in existing regimes and landscapes.

Fifth, the above leads us to cautiously confirm the framework by Smith and Raven [10]. We conclude that shielding, nurturing and empowering have proven to be generally useful concepts for gaining a richer understanding of the development of protective space in relation to solar PV in The Netherlands.

However, we make the following qualifications. First, shielding, nurturing and empowering are not temporally successive phases, but instead analytical abstractions of different types of concrete work by (networks of) innovation advocates. Especially shielding and empowering activities can take place simultaneously and, perhaps, are not as strictly distinguishable as we initially suspected. Second, the question of generality of these conclusions remains open. Whether the analytical utility of these concepts extends beyond the domain of solar PV, or beyond the Dutch national context, requires additional research. Specifically, a more detailed and comparative insider analysis of work done by such actor networks for different sustainable technologies and/or in different countries is necessary for finding patterns across cases. Third, we see a necessity for future studies covering shorter periods of time, in combination with focusing on specific periods where contestations and tensions are more clearly visible. Such studies, we expect, might be able to illuminate the processes that are still less understood, and relate these to periods where regimes and niches become intertwined. It is in these phases of transition processes, where the framework of Smith and Raven [10] may turn out to be the most useful.

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